

Measurement of Electron Antineutrino Oscillation Amplitude and Frequency via Neutron Capture on Hydrogen at Daya Bay

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This Letter reports the first measurement of the oscillation amplitude and frequency of reactor antineutrinos at Daya Bay via neutron capture on hydrogen using 1958 days of data. With over 3.6 million signal candidates, an optimized candidate selection, improved treatment of backgrounds and efficiencies, refined energy calibration, and an energy response model for the capture-on-hydrogen sensitive region, the relative $\bar{\nu}_e$ rates and energy spectra variation among the near and far detectors gives $\sin^2 2\theta_{13} = 0.0759^{+0.0050}_{-0.0049}$ and $\Delta m_{32}^2 = (2.72^{+0.14}_{-0.15}) \times 10^{-3} \text{ eV}^2$ assuming the normal neutrino mass ordering, and $\Delta m_{32}^2 = (-2.83^{+0.15}_{-0.14}) \times 10^{-3} \text{ eV}^2$ for the inverted neutrino mass ordering. This estimate of $\sin^2 2\theta_{13}$ is consistent with and essentially independent from the one obtained using the capture-on-gadolinium sample at Daya Bay. The combination of these two results yields $\sin^2 2\theta_{13} = 0.0833 \pm 0.0022$, which represents an 8% relative improvement in precision regarding the Daya Bay full 3158-day capture-on-gadolinium result.

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The neutrino mixing angle θ_{13} is one of the independent parameters of the three-neutrino oscillation framework and must be determined experimentally. It is an important input for the determination of other fundamental parameters, most notably, the lepton charge-parity violation phase δ_{CP} [1], the ordering of the second and third neutrino mass eigenstates [2], and the octant of the neutrino mixing angle θ_{23} [3]. Precise knowledge of this parameter is also critical

for flavor model building and for searches of new physics in the neutrino sector, such as nonunitarity of the Pontecorvo-Maki-Nakagawa-Sakata matrix [4–6].

Precise measurements of θ_{13} have been reported by the Daya Bay [7], RENO [8], and Double Chooz [9] reactor experiments, all of which operate at km-scale baselines and rely on the inverse β -decay (IBD) reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ to detect $\bar{\nu}_e$'s. These experiments were designed to use neutron capture on gadolinium ($n\text{Gd}$), $n + \text{Gd} \rightarrow \text{Gd} + \gamma$ s, as the primary channel to identify IBD neutrons. The high energy ($\sim 8 \text{ MeV}$) released in $n\text{Gd}$ capture enhances discrimination from the backgrounds produced by natural radioactivity, the overwhelming majority of which lie below 4 MeV. Moreover, the detectors use a Gd-loaded liquid scintillator (GdLS) target surrounded by an active liquid scintillator (LS) γ -catcher volume that significantly mitigates energy leakage which is the undetected energy deposited in nonactive volumes.

Oscillation measurements can also be carried out using a sample of IBD events where neutrons capture on hydrogen ($n\text{H}$), $n + {}^1\text{H} \rightarrow {}^2\text{H} + \gamma (2.2 \text{ MeV})$. However, the majority

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of the events in this sample occur in the LS γ -catcher region, where energy leakage effects are significant. Moreover, there is sizable background from natural radioactivity around the neutron capture signal of 2.2 MeV leading to larger systematic uncertainties.

These challenges notwithstanding, a precise and virtually independent oscillation measurement can be achieved with the $n\text{H}$ sample in Daya Bay. Rate-only oscillation measurements of θ_{13} with the $n\text{H}$ sample have been reported by this experiment [10] as well as by RENO [11]. The Double Chooz experiment reported a rate and spectral measurement where all capture targets were simultaneously considered [12].

In this Letter, the first measurement of the oscillation amplitude and frequency of reactor $\bar{\nu}_e$ at km-scale baselines using only the $n\text{H}$ channel is reported. The analysis is performed with 1958 days of data collected by Daya Bay from December 24, 2012 to August 30, 2017, resulting in an $n\text{H}$ sample that is 3.1 times of the previous one [10]. Two analyses relying on different calibration approaches, selections, background subtraction techniques, assessment of systematic uncertainties, and fitting methods are employed that yield consistent results. The large statistics combined with improvements in the understanding of the systematic uncertainties provides a $\sin^2 2\theta_{13}$ precision surpassed only by Daya Bay's $n\text{Gd}$ result [7]. An $n\text{H}$ -only measurement of the mass-squared difference Δm_{32}^2 is reported for the first time.

The measurement of θ_{13} presented here has almost no correlation with the one obtained with the $n\text{Gd}$ sample, as the two $\bar{\nu}_e$ samples are distinct and the systematic uncertainties are largely decoupled. The result thus increases confidence in the $n\text{Gd}$ result and improves the global precision of this important parameter.

In the three-flavor neutrino mixing framework for neutrino propagation in vacuum, which is an excellent approximation to Daya Bay's situation, the probability that an $\bar{\nu}_e$ produced with energy E is detected as an $\bar{\nu}_e$ after traveling for a distance L is given by

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}), \quad (1)$$

where $\Delta_{ij} \equiv 1.267 \Delta m_{ij}^2 (\text{eV}^2) [L(\text{m})/E(\text{MeV})]$, and Δm_{ij}^2 is the mass-squared difference between the mass eigenstates ν_i and ν_j .

Daya Bay uses eight identically designed antineutrino detectors (ADs) to detect $\bar{\nu}_e$'s emitted from six 2.9 GW_{th} reactor cores. Four ADs are deployed in pairs in two near experimental halls (EH1 and EH2), where the flux-averaged baseline is about 510 and 550 m, respectively, to constrain the $\bar{\nu}_e$ flux at a location where oscillation effects are small. The other four ADs in the far hall (EH3) with an ~ 1600 m flux-averaged baseline, sample the flux where the

term in Eq. (1) that is modulated by $\sin^2 2\theta_{13}$ is close to maximal. Each AD consists of three concentric cylindrical tanks: the inner acrylic vessel (IAV) contains 20 tons of 0.1% by weight GdLS, the outer acrylic vessel (OAV) contains 22 tons of undoped LS, and the outermost stainless steel vessel (SSV) contains 36 tons of mineral oil. A total of 192 eight-in-diameter photomultiplier tubes (PMTs) are installed in the mineral oil volume on the inner walls of the SSV. The energy and vertex of each detected event are reconstructed from the charge and time information collected by the AD PMTs. The energy resolution is about 9% at 1 MeV. The ADs in all halls are surrounded by two optically decoupled layers of water instrumented with PMTs that identify cosmic-ray muons. More details on the experiment's layout and detectors can be found in Ref. [13].

Measuring the oscillation parameters involves performing a relative comparison of the rate and energy spectrum of reactor $\bar{\nu}_e$ at multiple detectors. This requires correcting for instabilities and differences in energy response within each detector (spatial nonuniformities [14]) and establishing a common energy scale for all ADs. The two analyses used in this publication, referred to as A and B, begin from the reconstruction scheme described in Ref. [15], which relies primarily on spallation neutron (SPN) events tagged by $n\text{Gd}$ capture to calibrate the energy response and is optimized for the GdLS region. To improve the performance, most importantly in the LS region, analysis A calibrates the nonuniform energy response using the 2.2 MeV signal from $n\text{H}$ -SPN events. This analysis uses the fitted 2.2 MeV peak of $n\text{H}$ -SPN events to align the energy scale of the ADs. The fit is done with a new electromagnetic calorimeter function that decouples energy leakage and detector nonuniformity effects [16]. Analysis B uses the α energy peak from sequential β - α decays of ^{214}Bi - ^{214}Po from naturally occurring ^{238}U and ^{232}Th to map the nonuniform response. The response is normalized relative to the central GdLS volume so as to rely on the same energy scale calibrations used in Daya Bay's $n\text{Gd}$ analysis [7]. After calibration, the energy scale difference among ADs is less than 0.30% (0.35%) for analysis A (B), and the residual energy response nonuniformity within the ADs is less than 0.5% for each analysis.

The two analyses select IBD events by searching for a prompt positronlike signal in temporal and spatial coincidence with a delayed $n\text{H}$ -capture-like signal. Both selections start by removing events caused by spontaneous light emission from the PMTs using a set of improved cuts with negligible IBD detection inefficiency [7]. Events close in time to cosmic-ray muons are vetoed following the same criteria outlined in Ref. [10], and events with reconstructed energies smaller than 1.5 MeV are likewise rejected to suppress correlated β - α decays. The surviving prompt and delayed candidates are required to have a reconstructed energy < 12 MeV and within 3 times the fitted Gaussian

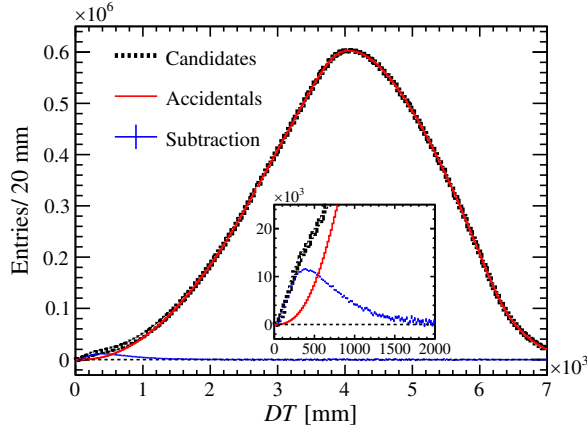


FIG. 1. DT distributions of all IBD candidates (black line), synthetic accidentals (red line), and the subtraction of the two (blue points). The latter consists predominantly of true IBD events with a small contamination of correlated background. An enlargement of the < 2000 mm region is shown in the inset.

width of each AD's 2.2 MeV neutron capture energy peak, respectively. Prompt-delayed event pairs are required to be within a coincidence time window of $[1, 1500]$ μ s. The analyses diverge here, with analysis A using the same methodology to identify prompt-delayed candidate pairs that has been used in past n H analyses described in Refs. [10,17,18]. Analysis B follows a complementary approach inspired by the n Gd IBD selection where prompt and delayed candidates are required to be strictly isolated within the $[1, 1500]$ μ s window [15].

At this point, a large amount of accidental background (explained below) remains given the lower energy released

in n H capture compared to n Gd. Further separation of the signal from the background is achieved by exploiting the tight spatial and temporal correlation of prompt and delayed IBD events. This is the main difference between the n H and n Gd analyses. Rather than imposing distinct time and distance separation cuts, as was done previously [10,17], prompt-delayed pairs are required to satisfy a combined $DT \equiv \text{distance} + \text{time} \times v < 1000$ mm cut in both analyses, where $v = 1000$ mm/600 μ s is close to the speed of thermalized neutrons. This combined cut is more effective at improving the signal-to-background ratio and reduces the relative detection efficiency uncertainty. The DT distribution of EH3 is shown in Fig. 1, which illustrates the importance of this cut as seen from the vast amount of accidental background that would otherwise remain in the IBD candidate sample. The selected DT cut value maximizes the sensitivity to θ_{13} , and the results of both analyses are found to be robust against variations in this cut value.

A summary of the IBD candidate, background, and signal rates in each AD can be found in Table I. It also reports the product of the muon veto and multiplicity efficiencies. The former is precisely determined from the known amount of live time vetoed, and the latter is estimated with negligible uncertainty from the measured rates of single events [10,15,18]. The dominant background consists of accidental events resulting from the coincidence of two uncorrelated singles predominantly from natural radioactivity. Both analyses generate a synthetic accidental background sample by randomly pairing events from the data that satisfy the IBD selection criteria. The accidental rates are calculated from the measured single rates

TABLE I. Summary of signal and backgrounds for analyses A and B. IBD rates are background subtracted. All rates are corrected for muon veto and multiplicity selection efficiencies $\epsilon_\mu \times \epsilon_m$.

	EH1-AD1	EH1-AD2	EH2-AD1	EH2-AD2	EH3-AD1	EH3-AD2	EH3-AD3	EH3-AD4
DAQ live time (days)	1536.624	1737.620	1741.214	1554.046	1739.010	1739.010	1739.010	1551.381
Analysis A								
IBD candidates	602 614	690 506	688 868	599 446	258 084	265 453	263 683	234 910
$\epsilon_\mu \times \epsilon_m$	0.6071	0.6044	0.6725	0.6724	0.9187	0.9179	0.9173	0.9186
Accidentals (day ⁻¹)	119.20 $\pm$ 0.04	117.58 $\pm$ 0.04	108.47 $\pm$ 0.03	104.17 $\pm$ 0.03	101.28 $\pm$ 0.03	106.73 $\pm$ 0.03	105.60 $\pm$ 0.03	104.78 $\pm$ 0.03
Fast neutron (AD ⁻¹ day ⁻¹)	2.78 $\pm$ 0.33		2.07 $\pm$ 0.23			0.18 $\pm$ 0.03		
⁹ Li/ ⁸ He (AD ⁻¹ day ⁻¹)	2.34 $\pm$ 1.01		2.83 $\pm$ 1.15			0.28 $\pm$ 0.10		
Am-C correlated (day ⁻¹)	0.05 $\pm$ 0.03	0.05 $\pm$ 0.03	0.04 $\pm$ 0.02	0.04 $\pm$ 0.02	0.02 $\pm$ 0.01	0.02 $\pm$ 0.01	0.02 $\pm$ 0.01	0.01 $\pm$ 0.01
Radiogenic neutron (day ⁻¹)				0.20 $\pm$ 0.04				
IBD rate (day ⁻¹)	521.36 $\pm$ 1.35	534.49 $\pm$ 1.33	474.64 $\pm$ 1.37	464.36 $\pm$ 1.39	59.57 $\pm$ 0.34	58.88 $\pm$ 0.34	59.02 $\pm$ 0.34	59.38 $\pm$ 0.36
Analysis B								
IBD candidates	518 082	595 250	619 406	540 947	268 557	264 137	270 823	234 572
$\epsilon_\mu \times \epsilon_m$	0.5228	0.5206	0.6028	0.6013	0.9183	0.9178	0.9177	0.9180
Accidentals (day ⁻¹)	120.05 $\pm$ 0.06	119.04 $\pm$ 0.06	111.02 $\pm$ 0.05	108.12 $\pm$ 0.06	107.64 $\pm$ 0.04	106.05 $\pm$ 0.04	109.74 $\pm$ 0.04	104.87 $\pm$ 0.04
Fast neutron (AD ⁻¹ day ⁻¹)	2.75 $\pm$ 0.17		1.97 $\pm$ 0.10			0.17 $\pm$ 0.02		
⁹ Li/ ⁸ He (AD ⁻¹ day ⁻¹)	3.18 $\pm$ 1.23		2.92 $\pm$ 1.09			0.19 $\pm$ 0.07		
Am-C correlated (day ⁻¹)	0.05 $\pm$ 0.03	0.05 $\pm$ 0.03	0.04 $\pm$ 0.02	0.04 $\pm$ 0.02	0.02 $\pm$ 0.01	0.02 $\pm$ 0.01	0.02 $\pm$ 0.01	0.01 $\pm$ 0.01
Radiogenic neutron (day ⁻¹)				0.20 $\pm$ 0.04				
IBD rate (day ⁻¹)	518.69 $\pm$ 1.53	532.81 $\pm$ 1.51	473.96 $\pm$ 1.33	465.61 $\pm$ 1.35	59.89 $\pm$ 0.34	58.80 $\pm$ 0.34	59.33 $\pm$ 0.34	59.21 $\pm$ 0.35

following the methods of Refs. [18] and [15] for analyses A and B, respectively. The distance, time, and DT distributions of the synthetic samples match those of selected candidates in the regions where these spatial or temporal separation cuts are significantly relaxed, and the full procedure is also validated using high-statistics simulations [10,18]. Accordingly, the accidental background subtraction procedure bears negligible systematic uncertainty.

Both analyses perform independent estimations of the fast neutron, Am-C, and ${}^9\text{Li}/{}^8\text{He}$ backgrounds using the previous methodology [10]. The only difference is the estimation of the fast neutron uncertainty. Analysis A compares the rates obtained by using the fitted high energy portion (> 12 MeV) of the IBD distribution to extrapolate below 12 MeV with a muon-tagged fast-neutron-like sample, whereas analysis B varies the energy range used for the normalization of the muon-tagged fast-neutron-like sample.

A new correlated background formed by neutrons produced in the spontaneous fission of ${}^{238}\text{U}$ or (α, n) reactions in PMT glass was recently identified [19]. Neutron recoils, or gamma rays produced in fission or deexcitation processes, can mimic the IBD prompt signal. The amounts of natural radioactivity and boron trioxide are measured in several samples of PMT glass with known weight. A GEANT4-based simulation is used to estimate the behavior of the neutrons with the fission information obtained from FREYA [20] and the (α, n) reaction cross sections obtained from the JENDL/AN-2005 database [21], whose consistency with measurement has been determined to be better than 10% [22]. The same estimation of this radiogenic neutron background is used for analyses A and B, as shown in Table I. Since this background originates in the glass of the PMTs, it is negligible in the GdLS volume and does not affect the $n\text{Gd}$ analysis [7] but has a visible impact on this study.

Table II summarizes all AD-uncorrelated uncertainties for both analyses. The total masses of GdLS, LS, IAV, OAV, and mineral oil were measured during the assembly of each AD, and the hydrogen mass fractions were also determined

for each chemical component. The uncertainties in these measurements are propagated to the uncertainty in the efficiency-weighted number of target protons [10]. The uncertainty introduced by the minimum prompt-delayed time separation cut of $1\ \mu\text{s}$ is reevaluated as in Ref. [10] and found to remain at 0.10%, while the $1500\ \mu\text{s}$ upper limit has a negligible inefficiency and thus no associated uncertainty.

The application of the 1.5 MeV prompt-energy cut introduces a variation of 0.08% in efficiency between the ADs as a consequence of residual variations in the energy scale after calibration. Variations in energy leakage between the ADs, mainly from geometric differences in nonscintillating volumes (the IAV and the OAV), contribute an additional 0.10%, yielding a total uncertainty of 0.13% for the prompt energy cut.

The uncertainty in the fit to the 2.2 MeV peak, as well as differences among ADs in terms of their $n\text{H}$ capture ratios, energy resolution, and energy leakage, introduce an AD-uncorrelated uncertainty in the efficiency of the delayed-energy cut that is estimated using the methods first introduced in Ref. [10]. Analysis A studies the AD-to-AD differences in ratio of $n\text{H}$ -SPN to $n\text{Gd}$ -SPN events, which is particularly sensitive to differences in capture ratio and energy leakage effects, yielding an uncertainty of 0.20%. Analysis B compares the ratio of the number of IBD candidates selected within 3 times the fitted Gaussian width of the 2.2 MeV neutron capture energy peak with the yield of IBD candidates in the larger energy range [1.5, 2.8] MeV to estimate a systematic efficiency difference between ADs of 0.24%. This approach is cross-validated with the $n\text{H}$ -SPN sample, which has larger statistics and better signal-to-background ratio, yielding consistent results.

For the DT cut, a new IBD sample obtained by relaxing this cut to 3 m and subtracting the synthetic accidental background is used as the denominator to estimate the DT cut efficiency of each AD. Both analyses estimated the uncertainty by extracting the 1σ spread of the resulting efficiencies for the eight ADs. The procedure was repeated on the samples of ${}^{214}\text{Bi}$ - ${}^{214}\text{Po}$ - ${}^{210}\text{Pb}$ cascade decays and $n\text{H}$ IBDs with a raised prompt energy cut $E_p > 3$ MeV, providing consistent results. The previous estimated uncertainty due to separate distance and time selections [10] suffered from double counting of statistical fluctuations leading to a significantly larger systematic uncertainty than that of the current DT cut.

As shown in Table II, the total systematic variation in the number of detected $\bar{\nu}_e$'s between detectors is estimated at 0.34% and 0.37% for analyses A and B, respectively. Efficiency uncertainties that are correlated among ADs cancel largely due to the relative near-far measurement and are thus not relevant.

An energy response model describing the relationship between the true $\bar{\nu}_e$ energy and the reconstructed prompt

TABLE II. AD-uncorrelated systematic uncertainties. The row “Target protons” accounts for relative differences in target mass, whereas the next four account for differences in various selection efficiencies among ADs.

	Uncertainty (%)	
	Analysis A	Analysis B
Target protons	0.11	0.11
Prompt energy	0.13	0.13
[1, 1500] μs	0.10	0.10
Delayed energy	0.20	0.24
Coincidence DT	0.20	0.21
Combined (ϵ)	0.34	0.37

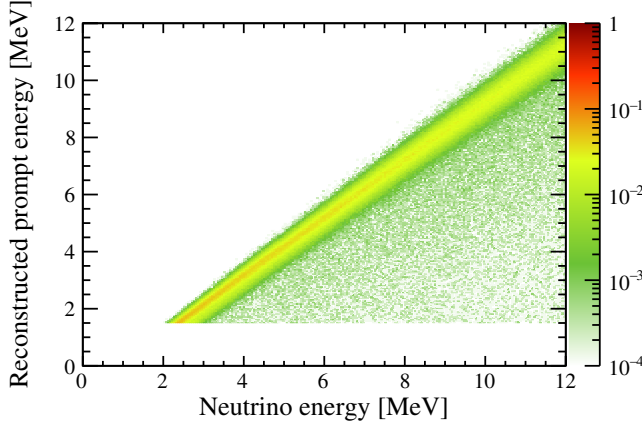


FIG. 2. Energy response matrix for an AD, relating the neutrino energy with the reconstructed prompt energy. The matrix is normalized for each neutrino energy bin, according to the actual energy-related selection efficiency. Events in the region away from the diagonal indicate the energy leakage effect.

energy, which is shown in Fig. 2, is constructed from a full GEANT4 [23] simulation to be consistent with the data. The model is used by both analyses with some minor differences highlighted below. An extensive calibration campaign including 59 different source and location points is used to tune and benchmark energy leakage effects in the simulation [24]. The main source of residual uncertainty concerning energy leakage is the slight difference in IAV and OAV geometries between ADs, whose effects are included in the oscillation fits via nuisance parameters. The model also accounts for nonlinearities in the conversion of the active energy deposit to scintillation light and the subsequent detection by the PMTs and their associated electronics. These nonlinearity effects are measured in the data using multiple γ and β sources [25] and are built directly into the model, with residual uncertainties accounted for via nuisance parameters in the oscillation fits. The cylindrical geometry of the ADs, the nonuniform PMT coverage, and the complex PMT angular acceptance induce a nonuniformity in the energy scale and its resolution, particularly in the LS region. The nonuniform energy scale is primarily corrected for in the data using the calibration procedures described earlier. Both analyses corrected the energy scale of the model to match the data, with analysis A applying an additional correction to also match the data in resolution and nonuniformity. Both analyses use their calibration precision as an uncertainty in their final fits. Finally, the model also accounts for small distortions in the prompt energy spectrum introduced by the DT cut, as a larger cut value, for example, can drive signal vertices to the edge of the AD where the response is slightly different from the center. Analysis B relies entirely on the simulation to correct this effect, while analysis A uses a data-driven correction derived from a comparison of the energy spectrum obtained with the nominal DT cut versus the one obtained with a loosened 3 m DT cut.

TABLE III. Best-fit results of the two analyses. “Rate only” denotes the situation where the fit relies only on the rate differences between the near and far ADs, whereas “Rate + shape” denotes the situation where both the rate and spectral information from all ADs is used. NO (IO) denotes the normal (inverted) neutrino mass ordering. Δm_{ee}^2 is the effective mass splitting defined in Ref. [27].

Analysis	Strategy	Results
A	Rate only	$\sin^2 2\theta_{13} = 0.0740^{+0.0068}_{-0.0069}$
		$\chi^2/\text{NDF} = 4.5/6$
	Rate + shape	$\sin^2 2\theta_{13} = 0.0759^{+0.0050}_{-0.0049}$
		$\Delta m_{32}^2 = (2.72^{+0.14}_{-0.15}) \times 10^{-3} \text{ eV}^2$ (NO) $\Delta m_{32}^2 = (-2.83^{+0.15}_{-0.14}) \times 10^{-3} \text{ eV}^2$ (IO) $\Delta m_{ee}^2 = (2.77^{+0.14}_{-0.15}) \times 10^{-3} \text{ eV}^2$ $\chi^2/\text{NDF} = 256.7/236$
B	Rate only	$\sin^2 2\theta_{13} = 0.0714 \pm 0.0071$
		$\chi^2/\text{NDF} = 1.55/3$
	Rate + shape	$\sin^2 2\theta_{13} = 0.0776 \pm 0.0053$
		$\Delta m_{32}^2 = (2.75 \pm 0.14) \times 10^{-3} \text{ eV}^2$ (NO) $\Delta m_{32}^2 = (-2.85 \pm 0.14) \times 10^{-3} \text{ eV}^2$ (IO) $\Delta m_{ee}^2 = (2.80 \pm 0.14) \times 10^{-3} \text{ eV}^2$ $\chi^2/\text{NDF} = 149.7/134$

The oscillation parameters are extracted from a χ^2 fit that takes into account the observed $\bar{\nu}_e$ rate and spectrum of each AD together with the survival probability of Eq. (1). Analysis A performs a simultaneous fit of the data in all ADs allowing for correlated variations in the rate and spectrum of the reactor $\bar{\nu}_e$ prediction to account for any mismodeling. Two independent fitting programs A.1 and A.2 are constructed. Analysis B follows a strategy similar to Ref. [26] where a prediction at the far hall is made directly from the observation at the near halls, minimizing the dependence on reactor $\bar{\nu}_e$ prediction models, confirming the results from analysis A. In both analyses, nuisance parameters are introduced in the χ^2 definition to account for reactor-related, detector-related, and background-related uncertainties. The best-fit values of both analyses are reported in Table III, where the fitting results of A.1 and A.2 are almost identical and are thus not repeated. The results of analyses A and B are consistent. There is also good consistency with other estimates, most notably the latest one from Daya Bay using the $n\text{Gd}$ sample [7].

The result of analysis A, which achieves a better precision, is chosen as nominal. Figure 3 shows a comparison between the observed and expected prompt energy spectra in the far hall with no oscillation and with the best-fit oscillation parameters of analysis A. Figure 4 shows the best-fit result and the 68.3%, 95.5%, and 99.7% confidence level allowed regions in the Δm_{32}^2 vs $\sin^2 2\theta_{13}$ plane. The statistical uncertainty of $\sin^2 2\theta_{13}$ and Δm_{ee}^2 accounts for about 47% and 64% of their total uncertainties, respectively.

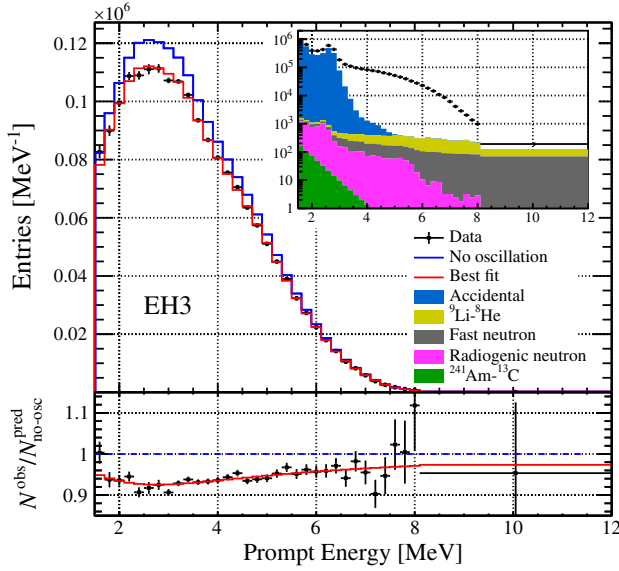


FIG. 3. Measured prompt-energy spectrum in EH3 after background subtraction with the best-fit and no-oscillation curves superimposed in the upper panel. The shapes of all candidates and backgrounds are shown in the inset. The lower panel shows the ratio of the observed prompt spectra after the background subtraction to the predicted no-oscillations one. The error bars are statistical.

The significant difference in selection criteria and in signal and background features makes the systematic uncertainties of this $\sin^2 2\theta_{13}$ measurement virtually independent from those of the $n\text{Gd}$ study. Using the result from analysis A, the combined, weighted-average value of $\sin^2 2\theta_{13}$ yields 0.0833 ± 0.0022 , which represents an 8% improvement in precision with respect to the $n\text{Gd}$

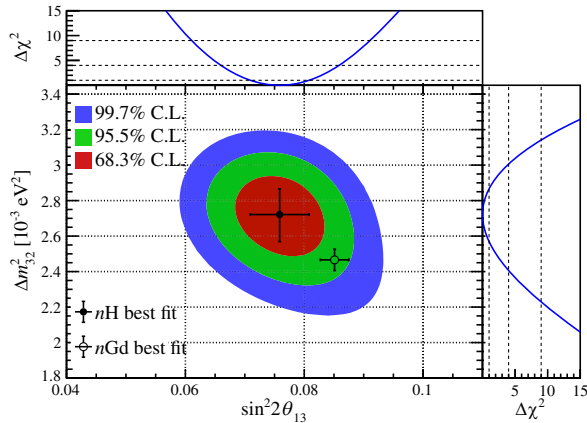


FIG. 4. The best estimate of the neutrino oscillation parameters $\sin^2 2\theta_{13}$ and Δm^2_{32} obtained by exploiting both the rate deficit and shape distortion of the $n\text{H}$ study are shown together with the allowed regions at different confidence levels. The best estimate from $n\text{Gd}$ sample [7] with normal mass ordering is shown too. The error bars include both the statistical and systematic uncertainties.

estimate alone that was obtained with 3158 days of data [7]. The combination of Δm^2_{32} results suffers from more correlations between the $n\text{Gd}$ and $n\text{H}$ analyses, requiring additional study.

In summary, a measurement of reactor $\bar{\nu}_e$ disappearance relying on both rate and spectrum is reported using a sample identified via neutron capture on hydrogen collected over 1958 days by the Daya Bay experiment. This work provides an estimate of $\sin^2 2\theta_{13}$ with an uncertainty of about 6.6% that is consistent with and virtually independent of Daya Bay's $n\text{Gd}$ result [7]. It also provides the first estimate of Δm^2_{32} from Daya Bay using the $n\text{H}$ sample, which is in good agreement with measurements relying on significantly different neutrino energies, baselines, and detection technologies, such as those from accelerator experiments [28–32]. This result enhances the global precision of both of these parameters and showcases techniques and lessons that can be relevant to other experiments, such as JUNO [33], which aims to determine the neutrino mass ordering and other oscillation parameters to high precision using the $n\text{H}$ channel. The energy response model and the measured prompt spectra used in the analysis are included as Supplemental Material [34].

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